PERFORMANCE OF THE TOWER OF HANOI AND ITS RELATIONSHIP TO THE PREFRONTAL CORTEX ACTIVITY

by

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ABSTRACT

The prefrontal cortex (PFC) is the area in front of the brain that makes humans cognitively aware of the environment. The PFC is responsible for vital aspects of cognition such as decision-making, attention, and most importantly executive function. Executive function relates abilities to differentiate thought processes, imagine future consequences of goals, work towards a concrete goal through strategy and several more cognitive aspects of conscientious thought. Through executive function, producing a movement goal creates motor planning. Motor planning is the process related to preparation prior to the movement itself. Levels of activity in the PFC can be monitored through brain imaging equipment such as the functional near-infrared spectroscopy (fNIRs). FNIRs is a non-invasive brain imaging technique where sensors emit light from a headband placed on a participants forehead. This technique measures the amount of infrared light that reflects from the PFC and through that researchers can convert that infrared light reading into oxygenated-hemoglobin (oxy-hb) levels of the brain. Having higher oxy-hb levels equate to a higher level of cerebral blood flow in the brain. Oxy-hb levels were compared between two different states: manual and computerized Tower of Hanoi (ToH). ToH is a cognitive planning game where a participant has to place different size discs together on multiple discs. The purpose of this study is to see if there are differences in oxy-hb between the manual and computerized ToH. Nine participants between the ages of 18-24 completed 20 trials of ToH, ten being manual and ten being computerized. All while being monitored by the fNIRS system. Results showed that eight out of the nine participants had relatively higher oxy-hb in the manual version of the ToH. This indicates that manual ToH results in a higher level of executive function which than results in a higher level of motor planning over the computerized ToH. Future studies hope to employ this study to expand knowledge about disorders with executive function deficits such as Developmental Coordination Disorder (DCD).

Chapter 1

INTRODUCTION

1.1 Prefrontal Cortex

The prefrontal cortex (PFC) occupies approximately one third of the entire cerebral cortex, which consists of the area anterior to the supplemental motor area and premotor cortex (8). The PFC is responsible for many behaviors that make humans cognitively aware of the environment. It is responsible for language, reasoning, decision-making, social interactions, planning, voluntary action, and attention along with many more (8,14,16). The PFC is integral in executive function which refers to higher level cognitive function involved in control and regulation of cognitive processes and goal directed future oriented behavior and planning (1,14). The PFC incorporates rich information absorbed through the environment and the greater options for behavior require appropriate intentional, decision-making and coordinative functions to deal with these possibilities humans have evolved to coordinate thoughts to prioritize or plan over our own internal goals (15). The PFC is most complex in primates, animals known for their diverse and flexible behaviors, and is the part of the brain that sends and receives projections from virtually all cortical sensory systems, motor systems and subcortical structures (14,15).

Executive function is vital in the prefrontal cortex, it is well known now that individuals who perform poorly on executive function tests have a frontal lobe deficit (1). Prefrontal cortex damage causes deficits in attention, working memory, response inhibition, voluntary action, planning, etc but spares object recognition long-term memory and visual analysis. PFC damage seems to devastate a person’s life. Patients have difficulty in sustaining attention, in keeping on task and seem to act on whims without regards to future consequence (14).

While the PFC is not critical for performing simple, automatic behaviors such as humans tendency to orient unexpected sound, which is known as bottom up processing. The PFC is important when top-down processing is needed which is when behavior must be guided by internal states or intentions (14). PFC is critical in situations when mapping between sensory inputs, thoughts and actions either are weakly established relative to other existing ones or are changing rapidly (14,15,16). Prefrontal cortex function is also vital in the acquisition of formal demands of tasks, guideline for complex, intelligent behavior (14).

Observations from patients with frontal lobe deficits or lesions shows that PFC patients who are able to execute simple routines in which they clear sensory cues could elicit a similar action but were unable to carry out a tasks where the patient needed to organize a series of objects because the patients kept going off tasks (14). Therefore, patients with a PFC deficit have trouble planning through an intelligent task.

1.2 Motor Planning

Motor planning refers to any process related to the preparation of a movement that occurs during the reaction time prior to movement onset (22). All actions revolve around having a motor goal that is selected as the desired outcome of a movement. Through the prefrontal cortex, humans observe the environment and select what they consider is important. Humans create a motor goal through the prefrontal cortex, from there humans create a movement program that identifies the movement, how it will end and how it should look during the process (18,22).

Another critical part of motor planning is attention, which is also an effect that comes from the prefrontal cortex (8,22). After the environment is taken in and all the sensory modalities are processed in the brain, attention is required to select an object of interest so that humans can mindfully choose what their next movement goal is. This deployment of attention is a prerequisite for motor planning as well as being a primary cognitive modality in executive function.

The main criterion to the formation of a motor movement involves utilizing appropriate movement task rules. These rules are ruled through the PFC (22). The PFC represents the association between a specific cue and the goal it indicates (14). Similarly, PFC may determine whether to inhibit a response to a movement goal as well as using mental imagery to imagine how to do a task (7). In Hanakawa's studies he compared finger-tapping sequences in a physical mode and a mental imagery mode while under a fMRI. Hanakawa's study showed that both finger tapping and mental finger-tapping innervated the motor cortices along with the frontal lobe: more in particularly anterior cingulate, medial superior frontal gyrus and the prefrontal cortex. These structures likely reflect "willed generation" otherwise known as motor planning of virtual motor commands and analysis of sensory signals (Hankawa).

Motor planning is necessary for all declarative and thought provoking movements. Through sensory receptors, humans gather information around them to create a movement goal and through the prefrontal cortex and other sensory/motor modalities a movement goal is produced. Therefore, if there is an increase in prefrontal cortex activation, researchers assume that there is also an increase in motor planning.

1.3 Tower of Hanoi

Problem solving in its simplest form is trial and error but this method is very inefficient. As human beings, we have the ability to use our prefrontal cortex to mentally plan movements before we even start a movement (2, 9). Through executive function, tasks that are constituted well-defined problems with definite solutions and allow systematic manipulation of complexity and planning demands are tasks that only humans are able to solve. An example of a problem with definite solutions and complexity is The Tower of Hanoi (ToH) which is a puzzle well known to test executive function and is widely used to test dysfunction of frontal lobe disorders (9,12).

The Tower of Hanoi is a puzzle that researchers are able to logistically solve and plan out. Researchers know the most optimal completion solution and through the Tower of Hanoi researchers could easily determine a control state of normalcy for regular people. The game consists of three pegs and in this study's case four discs. The disks are organized in a preset manner where the discs could be situated in a form of a tower or flat state. Tower form indicates that the largest is on the bottom and the smallest disc at the top. Flat form indicates that the discs could be on any of the pegs with the only condition that a smaller disc cannot be under a larger disc (21). The rules of the Tower of Hanoi are: only one disc can be moved at one time and a larger disc may not be placed on a smaller disc (12).

Researchers found that the Tower of Hanoi is sensitive to frontal lobe functions due to the usage of executive function in working memory (3, 21). The ultimate goal of the subject performing trials of the Tower of Hanoi is to figure out the sophisticated perceptual strategy (9). Kaller defines this as the appropriate strategy to minimize movements and time for the Tower of Hanoi. The strategy itself is to one: find the largest disk not in its goal position and make the goal to get it in that position, two: if there are any disks blocking the goal move, find the largest blocking disk and make the new goal move to move this blocking disk to the other peg, and three: if there are no disks blocking the goal move perform the goal move. Repeat this strategy until the puzzle is complete (9).

In this study, Welsh's revised Tower of Hanoi is used to reduce inconsistency of the Tower of Hanoi as a cognitive tool amongst all the trials. The original Tower of Hanoi was deemed to easy due to the fact the start position and end goal were always similar. Welsh's new Tower of Hanoi incorporated different start and end positions shown in *appendix A*. For example, instead of having all the discs on one peg to start with, Welsh put two of the smallest discs on the first peg, and the two larger discs on the third peg this format was deemed a flat because it resembled a flat line. Welsh created several variations of the Tower of Hanoi using the original tower start or end position but also utilizing the flat position. There were more puzzles and the difference made it so sophisticated perceptual strategy was harder to obtain

Along with Welsh's change in start and end positions, Welsh also created a difficulty scale amongst puzzles using number of minimum moves as an indicator of difficulty. The lower of the number of moves, the easier the difficulty of the puzzle and higher the number of the moves the harder the difficulty of the puzzle is show in *appendix B.*

With the addition of these changes, Welsh created a more reliable and consistent (in terms of being able to use the Tower of Hanoi as a cognitive tool) puzzle. Kaller defined the difference between the flat and tower state as goal hierarchy shown in table 1.

Table 1: In both Kaller and Welsh's study, each of the goal hierarchy's varied amongst the entire spectrum of difficulty.

Goal Hierarchy	Definition
Unambiguous	All objects are stacked on same peg (tower)
Partially ambiguous	Two or more disks are stacked on the same peg, at least one disk is placed on a different peg
Completely ambiguous	Each object is placed on a different peg (flat)

Most studies up to 2002 used the classic wooden versions of the Tower of Hanoi (2, 12). However, computerized versions of the test started to become more and more popular, which gave more immediate scoring, reporting of results, reduction of administration required and transcription of costs and errors (12). However, there are two disadvantages of the computerized version of the Tower of Hanoi, first: the wooden versions requires manual manipulation of the disks whereas the computerized versions requires manipulation of a mouse or keys on a keyboard making the visual constructive component and motor planning component of the test less evident (2, 12). Mataix-cols conducted an experiment comparing the classic wooden version of the ToH and computerized ToH comparing moves, time to solve, errors and several other observable changes. The result of this study showed that there was no difference between the manual and computerized versions of the Tower of Hanoi (12). This statement allows researchers to assume that manual and computerized Tower of Hanoi require the same level of cognition.

Liang (2015) compared the revised computerized Tower of Hanoi (21), which was a high cognitive task, to tapping (high motor task) and resting state while using the fNIRs system (more on this later) to look at oxygenated-hemoglobin differences in the Tower of Hanoi. The resultant of the study showed that there was no significant data between the resting and tapping states. There was no difference between simply resting and tapping which is a relatively high motor task. There was significant data between resting and computerized Tower of Hanoi but that was too be assumed since Tower of Hanoi is highly cognitive task. This fact shows that there is no difference in cerebral blood flow in the brain between resting and a high motor task. This dissipates any theoretical limitation that by moving a limb will increase oxygenated-hemoglobin in the fNIRS system.

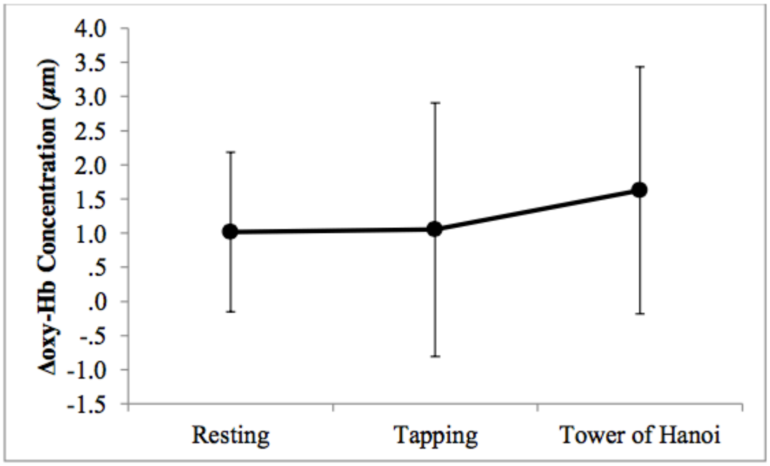


Figure 1: **Liang shows the very little difference in oxygenation concentration between resting and tapping.**

Table 2: Shows that low motor execution of a cognitive task is not a significant addition to a task. (11,12)

Condition	Significant/ Not Significant	Meaning
Manual Tower of Hanoi versus Computerized Tower of Hanoi	Not Significant	Level of difficulty is equal and cognition is equal
Tapping versus Resting	Not significant	Oxy-Hb between resting and tapping is equal

1.4 Functional Near-Infrared Spectroscopy

When stimulated, areas of the brain associated with cognition such as executive function undergoes a hemodynamic response otherwise known as an increase in local blood flow (5,17). Brain maps visualize this increase in cerebral blood flow, which allows researchers to see activation of the brain across a period of time (10, 17). An example of a brain map is functional near-infrared spectroscopy (fNIRS), which is a noninvasive brain imaging technique. This device is based on the facts that one: human tissues are relatively transparent to light in the infrared spectrum (650-1000 nanometers), two: near infrared light is absorbed by chromophores (pigmented compounds) or scattered in tissue, three: near infrared light is able to penetrate human tissues because the dominant factor in its tissue transport is scattering which is 100 times more probable than absorption and four: relatively high concentration of near infrared light in its tissue is due to the main chromophore hemoglobin located in small vessels (5, 10, 17).

FNIRS offers information about the oxygenation changes occurring at the venous blood level from veins, capillaries and arteries (17,20). Therefore, fNIRS uses flexible optic fibers to carry near infrared light to the brain and from the tissue around the brain. Through the fNIRS device, researchers are able to quantify these functions: (a) oxygenated hemoglobin (oxy-hb), deoxygenated hemoglobin (deoxy-hb), total deoxygenated hemoglobin and oxygen saturation (17, 20). When regional cerebral blood flow increase this action is evoked by astrocyte activation relative to the neurons activated which results in localized change in oxy hemoglobin and deoxyhemoglobin (17). Oxy-hb and deoxy-hb are the dominant absorbers of near infrared light in brain tissue (17). fNIRS is widely known to be used for frontal lobe studies in human newborns, children and adults as well as being relatively inexpensive compared to other brain imaging techniques such as fMRI or PET and it is flexible in changing to cerebral hemoglobin (5,17).

Researchers who use fNIRS fit a headband filled with 16 optodes with each optode having two wave lengths (5). This device is based on the baseline and task periods extracted from continuous data using markers from the fNIRS Software (5,20). The headband contains 4 light sources all of which are LED-infrared, 10 light detectors that create an array of 16 channels (3). The headband- source distance is approximately 2.5 cm and the distance for light to penetrate is approximately 1.5 cm beneath the scalp. Essentially, the oxygenation-hemoglobin, deoxygenation-hemoglobin, total hemoglobin and saturation of oxygen is dependent on the baseline data received from each participant. The blood oxygenation and volume changes from the 16 optodes are calculated used the Beer-Lambert Law for task periods in respect to the baseline (5). fNIRS values are standardized by measuring the optodes differently, the first eight optodes (1-8) are averaged to represent the left hemisphere of the prefrontal cortex while the last eight optodes (9-16) represents the right hemisphere of the prefrontal cortex.

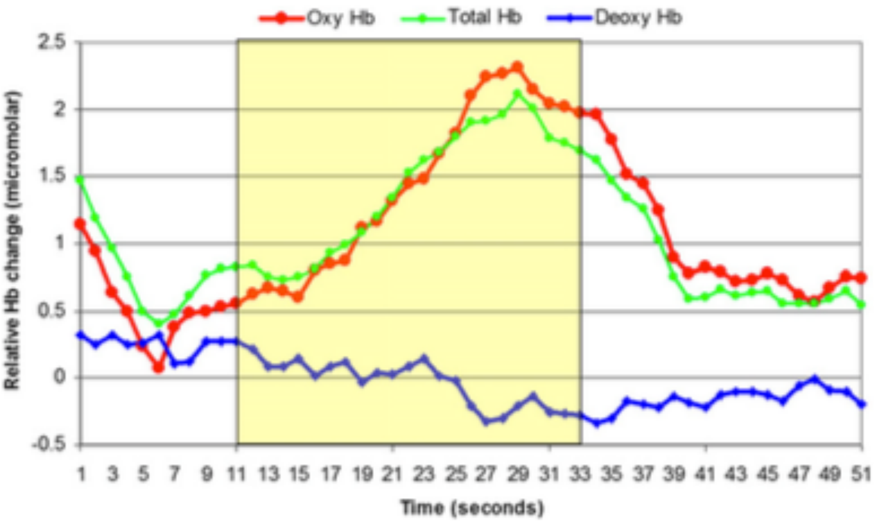
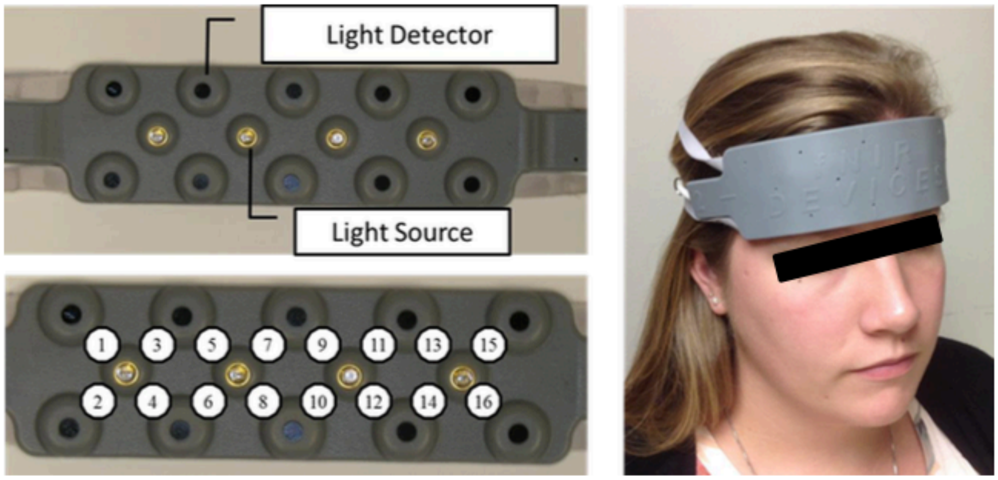


Figure 2: Looking at the red line this shows the hemodynamic time plot illustrating hypothetical changes in oxygenated hemoglobin.

Figure 2 shows a plot that shows time (s) versus relative hemoglobin change (micromoles or µmols) and shows change in total hemoglobin, oxy-hemoglobin and deoxygenated-hemoglobin. The general trend is as oxygenated hemoglobin increases, deoxygenated hemoglobin decreases and visa versa.



[redacted]

Figure 3: Shows headband used to collect oxygenation data (11)

1.5 Developmental Coordination Disorder (DCD)

DCD occurs in approximately 5-6% of children nation wide and is associated with impairments in fine and gross motor functions (13). DCD can lead to neuropsychological deficits, academics difficulties and behavior problems that lead to long-term issues in social and mental health and mainly stems from reduced activity in the prefrontal cortex and the structures involved in higher level of thought (4,13). Functional connections between the striatum and parietal cortex, areas involved in integrating sensory information in motor responses, are also altered in children with DCD (13). Children with DCD exhibit functional connectivity issues between brain regions involved in motor planning and function, and that neuropsychological problems underlie motor planning problems and attention (PFC) problems.

The motor performance of children diagnosed with DCD is characterized as clumsy and not planned out. In Debrabant's study, she found children with DCD couldn't focus on the ability to produce effective motor response timing. In children without DCD, they are able to use their PFC to analyze their environment, consciously and attentively acquire their movement goal and pursue their movement goal by visualizing it and having a motor plan to accomplish the task. Children with DCD however have trouble having efficient motor responses to extra stimuli (4,13). Children with DCD simply cannot assimilate perceptual timing and this impairs predictive motor responses, which also results in deficits in fine motor skill (4). Essentially every cognitive aspect mentioned earlier in this chapter is a deficit in children with DCD.

Chapter 2

SPECIFIC AIMS

2.1 Long Term Goal

Long-term goal of this study is to understand how much motor planning and executive function is required in cognitive tasks in children with developmental coordination disorder. The aim of this current study is to understand the differences between manual and computerized Tower of Hanoi and to see this difference through oxygenated-hemoglobin differences.

2.1.1 Aim 1

Replicate Mataix-Cols (12) study comparing manual and computerized Tower of Hanoi.

2.1.1.1 Hypothesis 1

There will be no difference in number of moves comparing the manual and computerized Tower of Hanoi.

2.1.1.2 Hypothesis 2

There will be no difference in time to solve comparing the manual and computerized Tower of Hanoi.

2.1.2 Aim 2

Examining oxygenated-hemoglobin differences between manual and computer Tower of Hanoi trials

2.1.2.1 Hypothesis 3

There will be differences between manual and computerized oxygenated-hemoglobin Tower of Hanoi trials.

Chapter 3

METHODOLOGY

3.1 Pilot study

Prior to the start of the study, undergraduate research students at the University of Delaware Developmental Motor Control lab were introduced to the Tower of Hanoi and learned how it relates to executive function. Researchers initially became accustomed to the software provided and performed pilot studies on each other and other people in the lab to use as test data. FNIRs program restrictions were analyzed through previous studies (6) and were incorporated into this studies methodology. Such things include setting up individual participant studies and knowing where and how to save the different files involved in the fNIRS software. Researchers were properly accustomed to use the Cognitive Optical Brain Imaging (COBI) studio software. COBI records light wave levels emitting off the fNIRS headband. COBI is also responsible for converting light waves into oxygenated hemoglobin waves.

Gomez's protocol for turning off the lights during recording of data was also implement just in case the extra stimuli would disturb the participant or pollute the light wave data from the fNIRS headband (6). Gomez's study used a winter ear-warmer to cover the fNIRS device onto the participant's forehead because of the necessity of the fNIRS headband to make contact with the subject's forehead. In this study instead of using a winter warmer, the headband holder was replaced with a du-rag (which covers the entirety of head and allows researchers to tightly secure the fNIRS device without being uncomfortable).

Once researchers were proficient with the fNIRS software and were able to keep the levels of infrared light between 400 and 4000 millivolts (keep range of light wave activation same for each participant). Researchers were able to change gains on the fNIRS device itself so in the case the majority of the light waves were skewed to one end of the spectrum or the other we are able to realign it into the range we needed. Taking Gomez's recommendation of the participant not moving his/her head we kept on using a stationary chair for the studies to prevent head movement, as well as telling the subject to limit head movements. Finally, researchers became proficient with the COBI software, which is used to analyze the raw data fNIRS, provided us to be used into something significant. In this case, the raw light readings from fNIRS were converted into three separate factors: oxygenated hemoglobin waves, deoxygenated hemoglobin waves and total hemoglobin waves. Through the oxygenated hemoglobin waves we transferred the raw numbers collected and transported them into excel sheets for each separate trial. For this study in particular there was a focus on the average oxygenated hemoglobin rate of all 16 optodes from the fNIRS headband in a certain trial.

3.2 Assigning Puzzles

Puzzles were assigned to two different sets (two sets so each participant didn't go through the same puzzles in the same order for computer and manual). Ten puzzles were picked from Welsh's study based on level of difficulty (21). Selection of puzzles was based on Welsh's recommendation of puzzles based on difficulty. Two different modalities were utilized: tower and flat (*appendix A and B for more information).* Five puzzles started off in a flat formation and five puzzles started off in a tower formation but the order was randomized through the ten trials. Within the two modalities, two puzzles were deemed easy, two puzzles were deemed intermediate and one puzzle was advanced based on the researchers interpretation of Welsh's revised Tower of Hanoi table (*appendix B)*. The level of difficulty was based on the minimum number of moves it required to complete said trial.

Mataix-Cols (12) study structure was replicated for the computerized and manual trials to coordinate with Welsh's separate trial forms. Participants were assigned sets (either set 1 or set 2) prior to the start of their research trials An example of which trials the subject would start off with would be: **Subject 1** start with **set 1** where the participant would start with manual trials. Once **Subject** 1 finishes 10 trials with set 1→ manual. **Subject 1** would than go on to **set 2** with computerized trials. **Subject two** would do **set 1**→ computerized than **set 2** → manual. Five subjects started with **set 1** and five subjects started off with **set 2**. Again **set 1** and **set two** contained the same puzzles just in a different randomized order.

3.3 Inclusion Criteria and Exclusion Criteria

Inclusion criteria: To be included in this study participants were: 1.) College aged student between (18-24), 2.) Physically and mentally healthy, 3.) Family has no previous mental disorders, 4.) No prior experiences with the Tower of Hanoi and 5.) All participants are right handed.

Exclusion Criteria: An exclusion questionnaire (general information sheet) was given to the participant prior to the study to confirm the participants met the inclusion criteria and did not have any of the following exclusion criteria: 1.) Previous head injury of any type or severity, 2.) a seizure disorder, 3.) Open wound on forehead, 4.) Unable to sit still for approximately one hour, 5.) Allergy to rubbing alcohol and 6.) The fNIRS device does not properly fit on the participant's forehead.

3.4 Participants

Study participants were 10 undergraduate students (5 male, 5 female) with a mean age of 21.2 and with a standard deviation of 1.5 and pass the inclusion criteria above.

Table 3: Shows the subjects gender, age and dominant hand (in this study everyone had the same dominant hand)

	Gender	Age	Dominant Hand
Subject 1	M	18	R
Subject 2	M	21	R
Subject 3	M	22	R
Subject 4	M	21	R
Subject 5	M	21	R
Subject 6	F	21	R
Subject 7	F	21	R
Subject 8	F	24	R
Subject 9	F	22	R
Subject 10	F	21	R

3.5 Protocol

Once participants were recruited for the study, participants came to the Human Performance Lab at the University of Delaware for data collection. Participants were given several sheets to fill out: IRB protocol, exclusion criteria questionnaire and Edinburgh Handedness Inventory. Edinburgh handedness Inventory is a questionnaire that informs the researcher, which hand the participant is dominant with (19). The exclusion criteria questionnaire was used to confirm the participant met all the requirements for the inclusion criteria and did not have any of the exclusion criteria above. The exclusion criteria questionnaire also doubled as a basic information sheet involving gender, height, weight, etc. The Edinburgh Handedness Inventory was also given to participants to see if the participants met the inclusion criteria for right-handedness. The Edinburgh Handedness Inventory was also used to indicate preferential motor skill and in how variance in motor proficiency on another task compares across groups with different scores on laterality (19). Following this paperwork, participants were informed on how to perform the Tower of Hanoi and that the ultimate goal is to finish the puzzle with the least amount of moves and least amount of time while try to also limit head movements.

3.6 Practice and Proficiency Test

After all the paperwork is complete, participants were given practice puzzles to become accustomed to the Tower of Hanoi. Five puzzles that were not in the study were given to the participant for both manual and computerized models. Participants were given as long as they needed to practice. It is noted however; no participant chose to go over the same practice puzzles twice.

Once the participant was confident enough in their ability to solve the Tower of Hanoi, the participant took a proficiency test where there were three difficulties one easy, one medium and one hard according to Welsh's study. (Look at *appendix* C)

If the participants solved these proficiency tests within the minimum moves allowed and under 60 seconds, the participant would than be viable for data collection.

3.7 Data Collection

Data collection started with wiping the fNIRS headband and participants forehead with alcohol swabs. Next, the participant was fitted with the fNIRS headband so that all 16 optodes fit on the participant's forehead. If the participant had too much hair around the forehead, researchers propped back the hair with a fNIRS headband and a du-rag so the fNIRS device snuggly fits on the participants head. Participants were close enough to the computer so head movement is minimized and far enough so the participant had proper posture.

Lights in the lab were than turned off and researchers turned on the fNIRS device and COBI studio software to visualize light waves. The gain was set so the range of light waves is in the range of 400-4000 millivolts. Than, researchers started a new experiment with the participant denoting the file under Max and Andrew's folder Subject 1, Subject 2, etc.

Once the light waves adjusted on the fNIRS software, the participant's brain-light waves at rest were baselined which is, what all of oxygenated/ deoxygenated hemoglobin is based off of. Since the base line of the light waves gets converted to oxygenated waves during COBI analysis, the same baseline is what oxygenated hemoglobin and deoxygenated hemoglobin are based off of (µmols). Once baselined, light waves that crossed the baseline in a positive direction was oxygenated-hemoglobin once converted. Light waves that crossed the baseline in a negative direction were deoxygenated hemoglobin (17).

If participant one was manual, researchers preset a PowerPoint presentation set with each end result of the puzzle. An example of a trial would be: a five second countdown→ researcher would introduce the start position for the given trial→ the participant would have however long he/she would need to solve the puzzle→ once the puzzle was complete researchers would start the rest timer of 25 seconds. This would repeat 10 times, once for each trial. In regards to how this procedure was marked in the fNIRS software, the other researcher would manually mark the beginning and end of each trial.

Figure 4: Shows how the manual trial would look but would only have 4 discs instead of the 8 shown above.

In the case of a computerized trial, researchers preset a PowerPoint presentation set but the start of the puzzle was shown first via Tower of Hanoi software that is available for use on the computer. The end result of each trial was printed out and was displayed right next to the computer. Therefore a computerized trial would go: five second countdown→ researcher would show the participant the end result on the piece of paper while simultaneously looking at the start position of the puzzle→ the participant had however long he/she would need to finish the puzzle→ once the puzzle was complete there is 25 second rest. This procedure is done again to completion. The marker system is the same as the manual markers system.

Figure 5: **Shows how a computerized trial would look**

While all of this was going on, the entirety of the trials was recorded via an iPhone 6 with the participant's knowledge to count for moves at a separate time. Out of the three things being looked at (moves required to solve puzzle, time to solve a puzzle, average oxygenated hemoglobin of all 16 optodes) moves was found via the videos. The time to solve (TTS) and average oxygenated hemoglobin for 16 optodes (oxy-hb in µmols) was calculated via the COBI software.

3.8 Data Reduction and Statistical Analysis

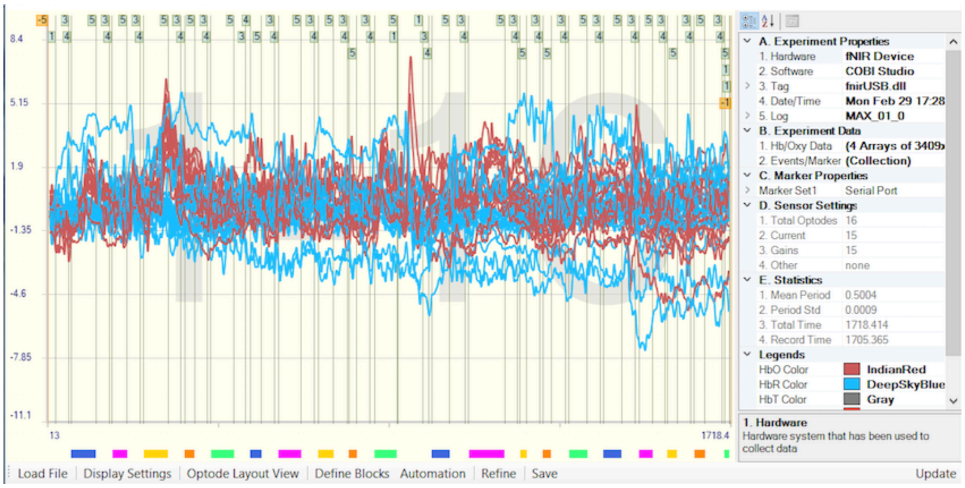
Data reduction started off with analyzing each of the videos and counting for moves. The moves were recorded for each trial and put into an excel sheet per subject. Moves recorded were looked at by trial and by subject. In this study averages were taken of all the trials amongst each subject but were split between manual and computerized. Ten trials of manual moves were averaged together and ten trials of computerized moves were averaged together and denoted in the figurative table shown below. (*Look at appendix D for actual data)*

Table 4: Example of how researchers looked at individual and average data

Average per subject	Moves-Manual	Moves-Computer	TTS-Manual	TTS-Computer	Oxy-Hb= Manual	Oxy-Hb= Computer
Subject 1	X	X	Y	Y	Z	Z
Average	X	X	Y	Y	Y	Z

Raw fNIRs data was converted to oxygenated-hemoglobin (µmols) from the infrared light waves via the COBI software. This information was than transported into two excel sheets per participant. One file had all manual trials and the other file had all computerized trials, these files were named **Subject X Set X Manual/Computer First/Second** an example would be Subject 1 Set 1 Manual First than the other file for subject 1 would be Subject 1 Set 2 Computer second.

In COBI studio, once raw data was opened and analyzed as a light graph, the data was refined to match the baseline level of light waves. This light wave data was than converted to oxygenated hemoglobin/ deoxygenated hemoglobin and total oxygenated hemoglobin waves. In this study, only oxygenated hemoglobin waves (µmols) were looked at. Through COBI software, times to solve and average oxygenated-hemoglobin (µmols) were calculated for each trial.



A. Experiment Properties	
1. Hardware	fNIR Device
2. Software	COBI Studio
3. Tag	fnirUSB.dll
4. Date/Time	Mon Feb 29 17:28
5. Log	MAX_01_0
B. Experiment Data	
1. Hb/Oxy Data	(4 Arrays of 3409
2. Events/Marker	(Collection)
C. Marker Properties	
Marker Set1	Serial Port
D. Sensor Settings	
1. Total Optodes	16
2. Current	15
3. Gains	15
4. Other	none
E. Statistics	
1. Mean Period	0.5004
2. Period Std	0.0009
3. Total Time	1718.414
4. Record Time	1705.365
Legends	
HbO Color	🟥 IndianRed
HbR Color	🟦 DeepSkyBlue
HbT Color	⬛ Gray

1. Hardware
Hardware system that has been used to collect data

Figure 6: shows raw oxygenation rates during time required to solve the puzzle

Markers were set to the correct time period and exported to excel labeled like: (Subject X Set X Manual/Computer First/Second) to make a master file for each trial. Time to solve was calculated by subtracting the end number in the time to solve column by the start number of the time to solve column. Oxy-hb rates were averaged for each optode and all 16 optodes were averaged together for a given trial time. This process was repeated for every trial and through this information researchers filled out the rest of table 4.

Once table 4 was filled out, researchers used a one-way ANOVA test to compare averages between manual and computerized trials for moves, time to solve and oxy-hb rates between all 10 subjects.

Chapter 4

RESULTS

4.1 Statistics

Participant 7's data became inconclusive when we realized that her data was contaminated due to human error during the fNIRS protocol. All participants completed the 4 disks Tower of Hanoi test with an average of 17.34 moves for the manual-moves (±3.00) and 16.23 for the computer moves (±2.05). The average time to solve (TTS) for the manual trials were 34.31 seconds (±10.08) and the average time to solve for computer trials were 28.15 (±8.15). The average oxygenation hemoglobin rates for manual trials were 2.24 (±1.28) and average hemoglobin rate for computer trials were 1.76 (±1.21) all of which is represented in table 5. For ANOVA, all results were analyzed at a α=0.05. F= F ratio in ANOVA and ns= not significant.

Table 5: Shows average moves, TTS and oxy-Hb for all participants

Condition	Moves-Manual	Moves-Computer	TTS-Manual (s)	TTS-Computer (s)	Oxy-Hb-Manual	Oxy-Hb-Computer
Mean	17.34	16.23	34.31	28.15	2.24	1.76
Standard Deviation	3.00	2.05	10.08	8.15	1.28	1.21

4.2 Moves

Figure 7 shows the average moves required to accomplish the Tower of Hanoi out of all subjects regardless of which method the participant started first. No significant difference was found between the manual moves and computerized move trials (p=0.44).

A one way ANOVA of manual Tower of Hanoi moves yielded no significant differences between computerized Tower of Hanoi moves F=. 63 ns. The means and standard deviation is represented in table 5.

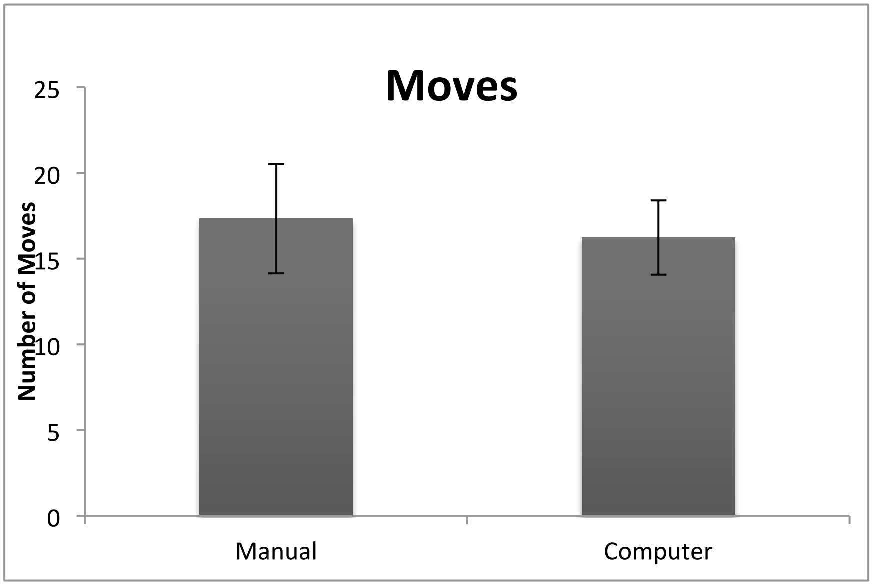


Figure 7: Average moves required in college-aged students during manual and computerized trials (bars represent standard deviation).

4.3 Time to Solve

Figure 8 shows the average time to solve required to accomplish the Tower of Hanoi out of all subjects regardless of which method the participant started first. No significant difference was found between the manual moves and computerized time to solve trials (p=0.21).

A one way ANOVA of manual Tower of Hanoi time to solve yielded no significant differences between computerized Tower of Hanoi time to solve F= 1.7 ns. The means and standard deviation is represented in table 5.

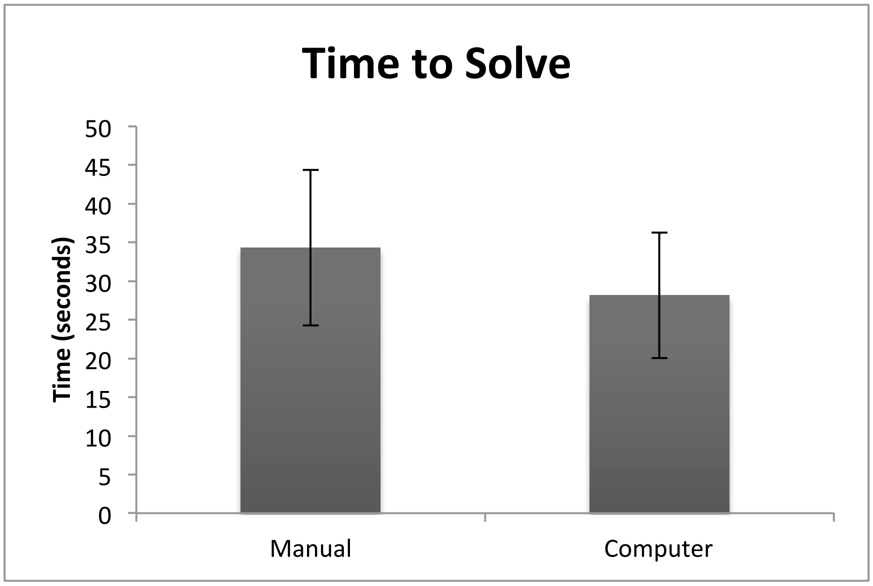


Figure 8: Average time to solve required in college aged students during manual and computerized trials (bars represent standard deviation).

4.4 Oxygenated-Hemoglobin Rate

Initial analysis was also one-way ANOVA, which resulted in figure 9 and at first analysis there was not a significant difference between computerized and manual Tower of Hanoi oxygenated-hemoglobin trials (p=. 42).

First analysis showed a one way ANOVA of manual Tower of Hanoi oxygenated-hemoglobin yielded no significant differences between computerized Tower of Hanoi oxygenated-hemoglobin F= 0.7 ns. The means and standard deviation is represented in table 5.

Second round of data analysis resulted in different viewing of the same data. If there were no differences between manual and computer, we would expect that for half the participants, activation would increase and for half the participants, activation would decrease between conditions. In our participants, 8 increased activation from manual to computer and 1 decreased. These proportions are significantly different at p= .012 using a chi squared analysis.

Table 6: Represents the data from the chi square analysis

Subject	Oxy-Hb-Manual	Oxy-Hb-Comp	Increase/ Decrease
Subject 1	0.50	-0.096	-
Subject 2	2.70	1.99	-
Subject 3	1.82	3.18	+
Subject 4	4.71	3.40	-
Subject 5	2.17	1.69	-
Subject 6	1.16	0.97	-
Subject 7	-	-	
Subject 8	1.22	0.55	-
Subject 9	2.52	1.24	-
Subject 10	3.36	2.89	-

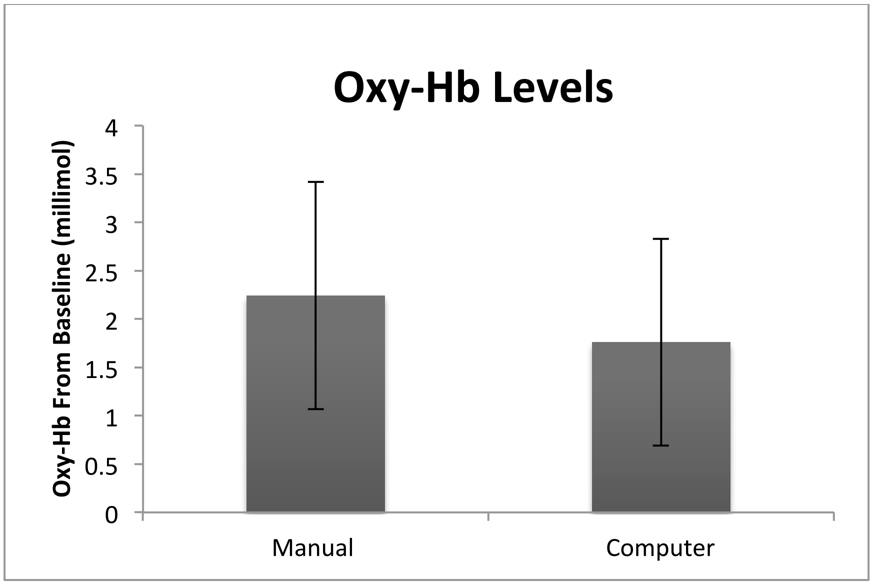


Figure 9: Average oxygenated-hemoglobin levels in college aged students during manual and computerized Tower of Hanoi trials (bars represent standard deviation)

The general trend across all figures shows that the manual trials on average required more moves and longer average time to solve for all trials. However, like Mataix-Cols study, there was no significant data with an alpha level of α=0.05 between manual and computerized moves and time to solve trials. The trend stated in the specific aims that there would be differences in oxy-hb between manual and computerized trials was correct. However, with an alpha level of α=0.05 there was no significant difference oxy-hb in the ANOVA results. However, in the chi-squared results differed from ANOVA. Manual and computerized Tower of Hanoi oxygenated-hemoglobin (μmols) trials were strongly positively correlated p=. 012.

Chapter 5

DISCUSSION

5.1 Analysis of Data

The prefrontal cortex is integral for executive function, which refers to higher-level cognitive function involved in control and regulation of cognitive processes, and goal directed future behavior and planning (Alvarez, Miller). Motor planning refers to any process related to the preparation of a movement that occurs during the reaction time prior to movement onset (22). Therefore, motor planning is more prevalent when there are higher levels of prefrontal cortex activation thus higher level of executive function. The more a person requires a higher level of motor planning, the more the person needs a higher level of pre frontal cortex activation.

Examining the differences between computer and manual moves and time to solve were replicated via Mataix-Cols (12) study and the results that came from this study proved Mataix-Cols study as well. There was no significant difference between manual and computerized Tower of Hanoi for moves and time to solve. Therefore the results for moves and time to solve did support hypothesis' 1 and 2.

However, we did see significant differences between computer and manual oxygenated hemoglobin via the chi-squared test. This does support hypothesis 3 that the manual version of the Tower of Hanoi will require a higher level of oxygenated-hemoglobin (micromoles) than the computerized version of the Tower of Hanoi. The general trend showed that for a given person, there was a higher level of oxygenation-hemoglobin activation for manual trials and that almost always there was a decrease in computerized trials.

The rationale for the increase oxygenation in manual is that the trials and conditions were controlled for both manual and computerized trials. The level of difficulty and amount of cognitive activity is the same for both computer and manual trials. The idea is that the extra-oxygenated hemoglobin comes from the increased need of motor planning for manual trials due to the increased motor execution. Because activation levels varied between subjects, we were able to see trends if increasing activation in manual by using the chi squared test.

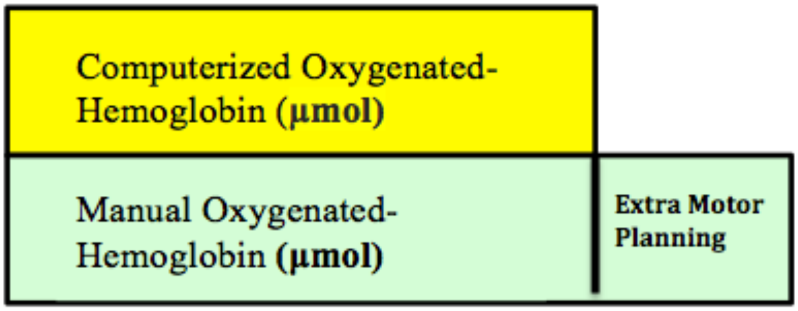


Figure 10: Graphical representation of what is assumed to have happened between manual and computerized ToH.

Relative to this rationale, this shows that there is an increase in prefrontal cortex activation for manual trials, which shows that there is higher executive function in these manual trials compared to computerized trials. Mataix-Cols (12) proved that there were no significant differences between manual and computerized ToH when it comes to moves and time to solve. Since cognitive levels were controlled for both computerized and manual trial, we assume that manual and computerized ToH require the same level of cognition. The plan of attack for the participant, when to move your hand and which part to move the puzzle creates extra activity and is due to motor planning. Hanakawa’s (7) study showed that mental practice, imagining what is to come, innervates the prefrontal cortex. Liang’s (11) study compared resting state, tapping and computerized ToH. Since there was no significant differences in oxy-hb between resting and tapping, this statement rules out there could be more oxy-hb in manual trials just because a participant is moving their fingers.

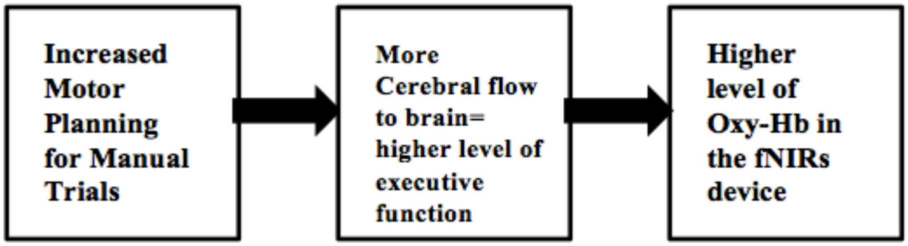


Figure 11: Flow chart of assumed chain of events for manual trials of the Tower of Hanoi

5.2 Future Directions

This experiment suggests that there is a higher level of motor planning for manual trials, which results in higher executive function through the prefrontal cortex. The next step would be to recreate this procedure with a much larger sample size and if the data is still relevant for oxygenated-hemoglobin between manual and computerized trials.

The assumption of higher level of motor planning for manual trials could be used when any population processes new information, learns something new or when a person would read how to do a conscious task. Instead of studying by staring at a computer screen, there is a potential of capability to stimulate the prefrontal cortex more when consciously writing things down instead of typing on a computer. Also, if a person reads how to do something on the Internet, this assumption of higher motor planning in manual contexts could mean reading a book or copying down a task from a book could potentially cause a higher level of executive function.

5.2.1 Developmental Coordination Disorder: Next Step

The next step after that would be to see how this control group would compare to people with developmental disorders such as children with developmental coordination disorder. Children with DCD exhibit functional connectivity issues between brain regions involved in motor planning and function (4, 13). Children with DCD have reduced capacity in their prefrontal cortex and they cannot assimilate perceptual timing, which impairs motor responses.

The step following a larger scale control study would be pilot testing on children with and without DCD. Children with DCD largely have deficits in prefrontal cortex activity and by using the fNIRS and simpler Tower of Hanoi study; there is a possibility of determining a numerical value of oxygenation-hemoglobin differences between children with and without DCD. DCD is a developmental disorder that is related to cerebral palsy and Parkinson's. The deficits in motor timing can affect children with DCD all the way until they are adults. By having a numerical value and representation of the lack of motor planning and executive function via oxy-hb, researchers can work with occupational and physical therapist to help children and adults with DCD to figure out an appropriate regiment to improve off of.

A future direction that could happen with the Tower of Hanoi is to use it as a transfer design. Organize a pilot study of children with and without DCD, where they undergo a simpler version of the manual Tower of Hanoi and solely look at oxygenated-hemoglobin. Researchers would have children undergo acquisition trials for the Tower of Hanoi over a period of a few days. Then the children with DCD could go to occupational therapy for a short training regiment. Following a couple of days, researchers could see if there was any improvement in the children through a transfer test using the Tower of Hanoi but use a puzzle that was not used during acquisition. If this procedure doesn't work, the occupational therapist could try different things and this structure could be repeated to see what helps children with DCD improve motor planning and executive function.

5.3 Limitations

There was only a sample size of 9 (originally 10) due to the time constraint of the study. Potentially with a larger sample size the results would not have been as good for the oxygenated-hemoglobin comparison data or the data would not have been replicated and there could have been a significant difference between manual and computerized trials for moves and time to solve for trials.

Another limitation was the size of the headband; we had to exclude three participants due to the headband and its need for a certain kind of forehead shape. If a participant's forehead were too rounded at the top, the headband would not properly sense the optodes.

Another limitation was the way I examined the data, if I had more time I could examine prefrontal cortex activity in a more split region. Rather than averaging activity of all sixteen optode channels. A possible alternative to data would be examining the data depending on approximate zone of more particular parts of the

PFC. For example, a potential step in the future could be examining channels that look at the lateral, medial, left or right PFC. The prefrontal cortex is a vast part of the brain and by potentially looking at something like just the ventolateral region of the prefrontal cortex, which controls a part of working memory (16). Researchers could see if participants are learning anything during the process of the study.

A potential big change that I would recommend happen if this study were to be replicated is to improve the experimental protocol. Researchers should increase the amount of practice participants would get in the very beginning of the study along with putting a time limit on each trial to eliminate some outliers. In general, if participants are more on the same page in terms of ability to do the Tower of Hanoi, I believe the results will look even better.

Another limitation is solely looking at oxygenated-hemoglobin instead of looking at deoxygenated hemoglobin and total hemoglobin as well. A way a researcher could confirm the data makes sense is compare oxygenated and deoxygenated hemoglobin (deoxy-hb) charts. There is an inverse relation between oxygenated and deoxygenated hemoglobin so if the oxygenated wave moves up from baseline, the deoxy-hb wave in theory would dip down below baseline at the same rate. This would just be another parameter to maximize data results and prove a hypothesis.

Chapter 6

CONCLUSION

The results of this study showed that there is a significant increase in oxygenated hemoglobin in college aged males and females for manual version of Tower of Hanoi compared to a computerized version of Tower of Hanoi. This finding helps support the theory that there was more motor planning in manual trials, which increased cerebral blood flow in the brain resulting in higher executive function. All of this was represented by increased oxygenated-hemoglobin in the functional near-infrared spectroscopy device. Also, Mataix-Cols (2002) study was replicated and confirmed. The numbers of moves and time to solve between manual and computerized Tower of Hanoi have no significant difference.

Small sample size and variation between participants limited the findings of the current study. Future studies could include studies involving a larger sample size or a younger population group. Ultimately, to progress this study to children with developmental coordination disorder to potentially help find ways to promote motor planning and executive function in children who have deficits in these vital cognitive processes.

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Appendix A

Welsh's Revised Tower of Hanoi

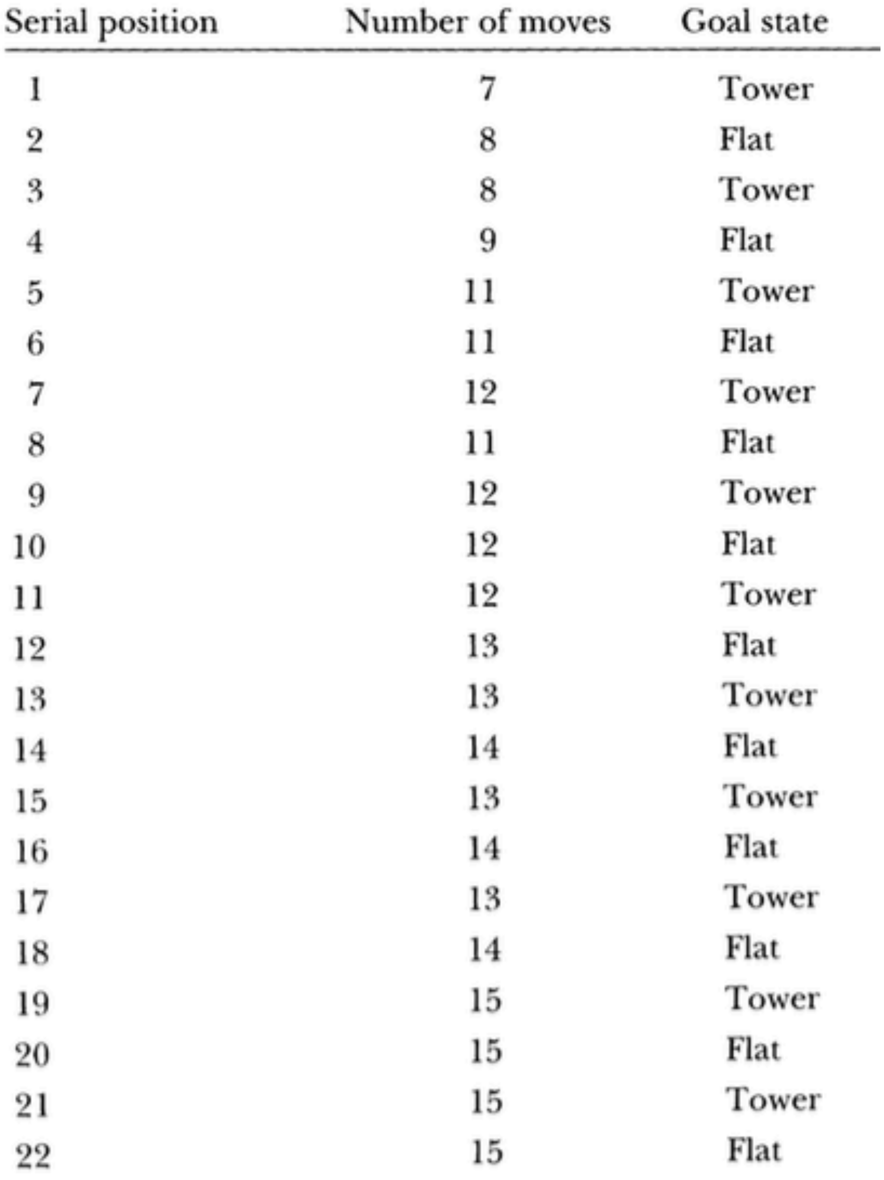
1.

2.

3.

Appendix B

Welsh's Level of Difficulty



Serial position	Number of moves	Goal state
1	7	Tower
2	8	Flat
3	8	Tower
4	9	Flat
5	11	Tower
6	11	Flat
7	12	Tower
8	11	Flat
9	12	Tower
10	12	Flat
11	12	Tower
12	13	Flat
13	13	Tower
14	14	Flat
15	13	Tower
16	14	Flat
17	13	Tower
18	14	Flat
19	15	Tower
20	15	Flat
21	15	Tower
22	15	Flat

Appendix C

Proficiency Test Results

	Test 1		Test 2		Test 3		
Subjects	**Time (s)**	**Moves of 20**	**Time(s)**	**Moves of 24**	**Time(s)**	**Moves of 25**	**Pass/fail**
1	17.27	9	57.38	24	55.64	17	Pass
2	15	9	21	13	37	25	Pass
3	52	20	52	23	47	20	Pass
4	26.31	11	35.68	13	58.67	25	Pass
5	11	11	30	24	22	7	Pass
6	17	9	42	23	31	14	Pass
7	15	11	45	21	33	14	Pass
8	16.73	9	20.81	13	55	23	Pass
9	14	9	51	24	33	17	Pass
10	19.21	10	19.76	13	29.41	19	Pass
Average	20.35	10.8	37.463	19.1	40.17	18.1	

Appendix D

Complete Average Data Set

Averages	Moves-Manual	Moves-Computer	TTS-Manual	TTS-Computer	Oxy-Hb-Manual	Oxy-Hb-Computer
Subject 1	16.8	15.5	43.9355	36.1286	0.4964	-0.0957
Subject 2	13.6	14.7	19.9018	22.8485	2.7001	1.9901
Subject 3	17.1	15.3	35.0809	31.2114	1.8224	3.177
Subject 4	19	19.4	38.6341	35.3779	4.7124	3.4029
Subject 5	18.5	16.2	33.263	15.4002	2.1748	1.689
Subject 6	15	14.2	27.6097	23.3466	1.1608	0.967
Subject 7	-	-	-	-	-	-
Subject 8	13.9	14	20.097	22.3496	1.2196	0.5529
Subject 9	19.1	19.2	47.4595	40.5664	2.5233	1.2395
Subject 10	23.1	17.6	42.8106	26.1249	3.3573	2.89298
Average	**17.34**	**16.23**	**34.31**	**28.15**	**2.2408**	**1.7573**